Optimization in civil engineering

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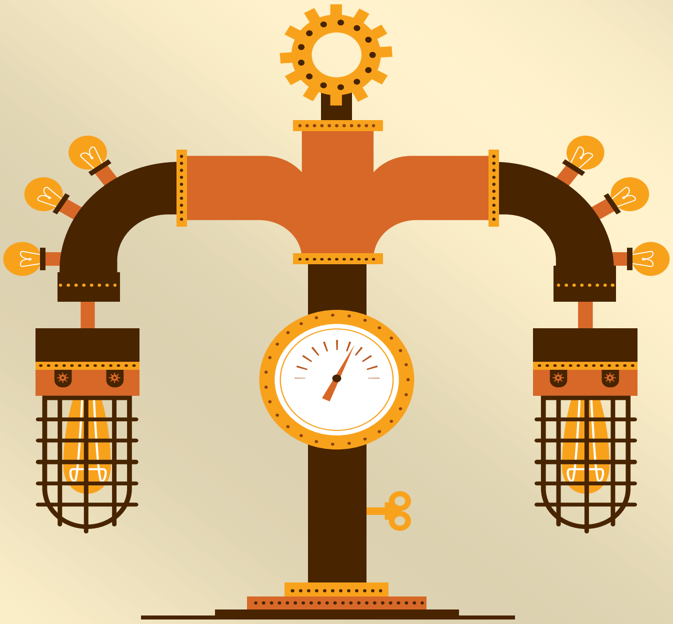

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“Water is the Driving Force of All Nature.”

—Leonardo da Vinci

1. Introduction:

The application of optimization to real word engineering problems is very recent, the main reason being the complexity of mathematical models, described by non-linear functions and generating a non-convex space of solutions. In order to beat the difficulties, researchers have more interest in advanced optimization techniques. Maintenance of structures, **energy efficiency and water consumption** are examples of areas where optimization techniques should be applied to make civil engineering a sustainable domain that boosts economies while protecting the environment and implementing social criteria, and thus balancing conflicting objectives.

2. Definition:

By optimization, we mean the act or operation by which we make a process or system **as good as possible**. In other words, an optimization problem is defined as finding the best solution in a pool of all feasible solutions. In many engineering problems, the optimal solution is the minimum or maximum value of the objective function of the problem, which is generally the cost. Sometimes, the optimization problem might need multiple objective functions and might have multiple solutions.

The first step is usually to define the decision variables, objectives and constraints of the problem. This will then guide what aspects of the system got to be modeled and what data is required to take into consideration all of the decision variables and that will provide information for all of the objectives and constraints. Multiple potential solutions to the problem form the solution space and the optimization algorithm guides the search of this solution space towards the global optimum. The size of the answers space depends on the amount of decision variables and the number of choices available for those decision variables. More complex problems are often described as having a more ‘rugged’ solution space, meaning the optimization algorithm is more likely to get trapped in local optima and can have more difficulty finding the global optimum. When a single objective optimization algorithm is used, there is only one optimal solution, while in multi objective optimization, a Pareto front will be developed with multiple solutions representing different trade-offs between the objectives. Most optimization algorithms have parameters that need to be defined by the user, such as the number of generations or iterations and the population size in evolutionary algorithms.

3. Optimization algorithms used in civil engineering:

Genetic Algorithms (GA), Harmony search (HS), Artificial Bee Colony (ABC), Tabu Search (TS), Teaching– Learning-Based Optimization (TLBO), Particle Swarm Optimization (PSO), Big bang – big crunch (BBBC), and Charged System Search (CSS)…

These are only a few examples, not particular to one field of research. Different optimization algorithms will be more suited to different problems, and the set up procedure depends on the algorithm. The optimization algorithm used in the example we study below (which is one of the two cases studies by Blinco et al [1]) is the Non-dominated Sorting Genetic Algorithm II, along with a hydraulic solver (EPANET) and a hydrologic solver (MUSIC).

How does it work?

NSGA II is a searching algorithm for finding a non-dominated solution of multi-objective optimization problems. This algorithm is known for three main features:

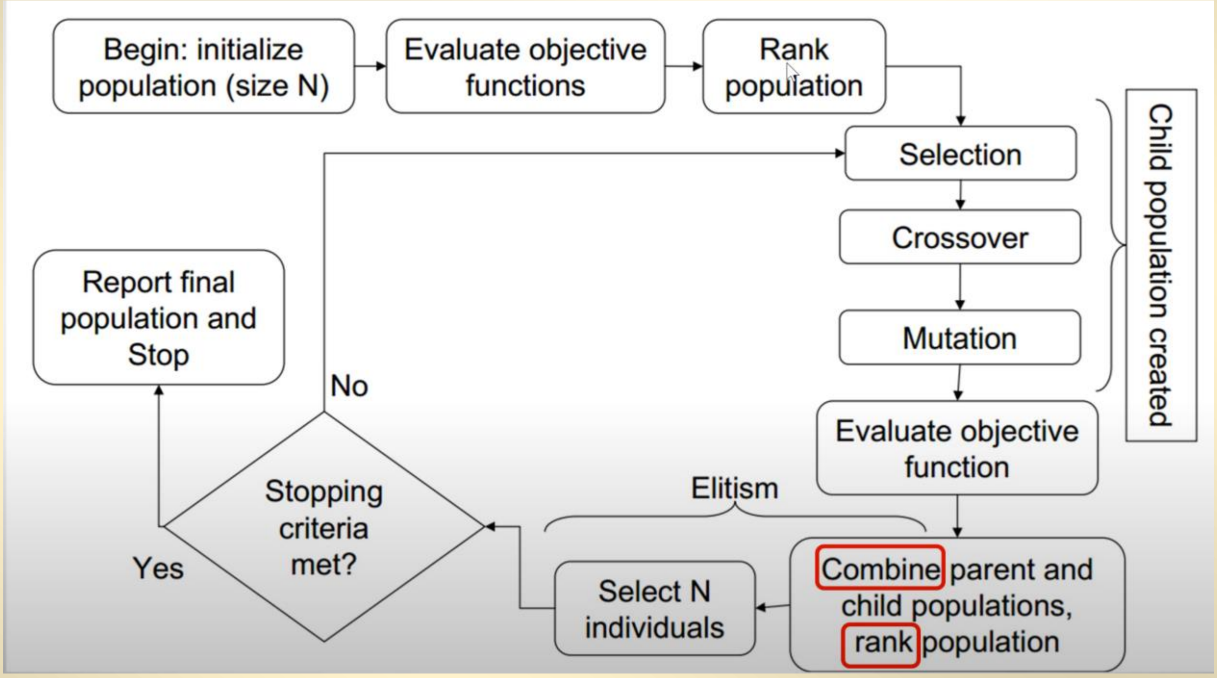
A Non-dominated sorting, where all the individuals are sorted according to their level of non-domination

An Elitism which stores all the non-dominated solution, enhancing fast converging properties

A Crowding distance that emphasizes on less crowded solutions to maintain the diversity and spread of the solutions.

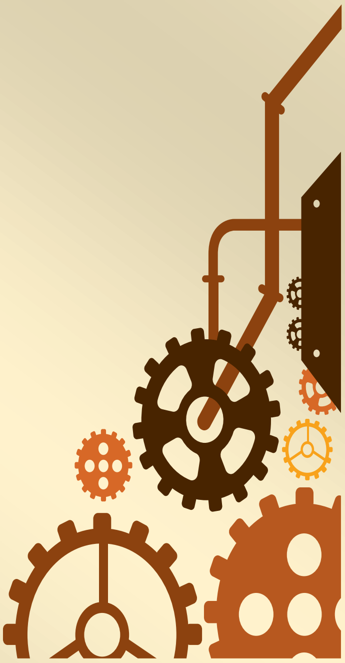
The procedure of NSGA II is the following:

First, randomly generate the first generation sized N. then calculate the objective functions of the first generation. Finally, sort population by non-dominated sorting approach.

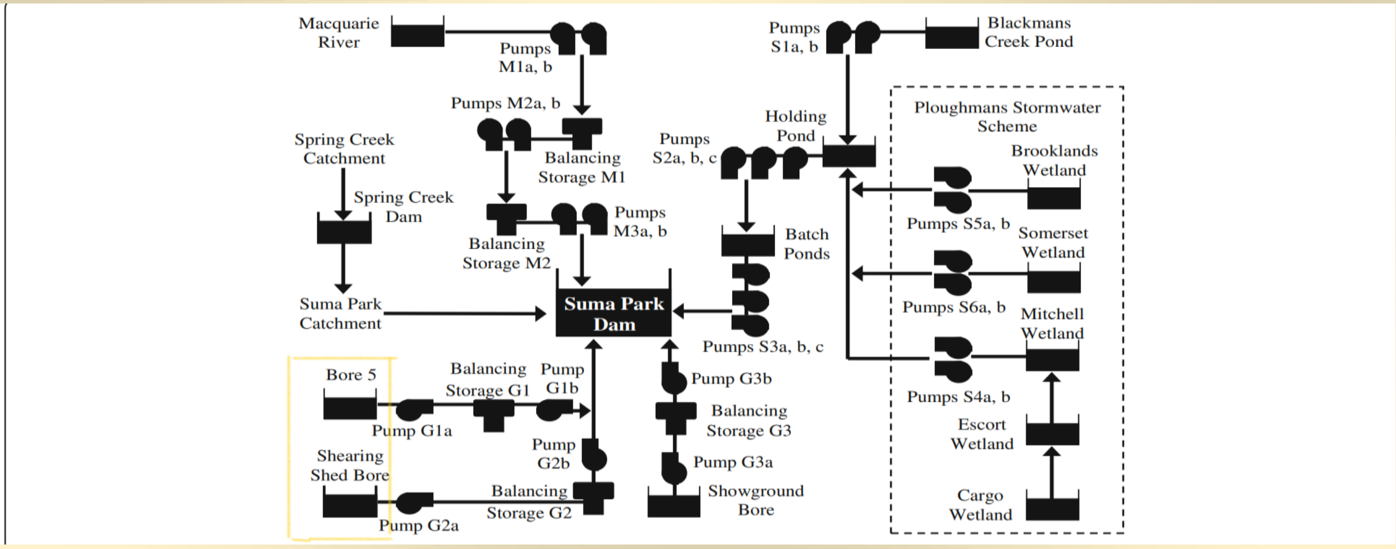

Begin: initialize population (size N)
Evaluate objective functions
Rank population
Selection
Crossover
Mutation
Child population created
Evaluate objective function
Combine parent and child populations, rank population
Elitism
Select N individuals
Stopping criteria met?
No
Yes
Report final population and Stop

4. A real world application

First, the problematic?



Orange is a rural town in the state of New South Wales, Australia. The water system serves a population of around 36,800 people with an average annual demand of roughly 5,400 ML. The majority of water supply is from the local surface water catchment, which culminates in the roughly 19,000 ML Suma Park reservoir. Australia experienced severe drought between 2000 and 2010, and Orange was one of the hardly affected. Even with severe water restrictions almost halving the town's demand, Orange had less than two years of water supply heading into summer of 2009 and was relying only on surface water catchments. This prompted the Orange City Council to diversify their water supply, so they developed two storm water harvesting schemes and a long pipeline from an adjacent catchment, as well as re-opening several groundwater bores.

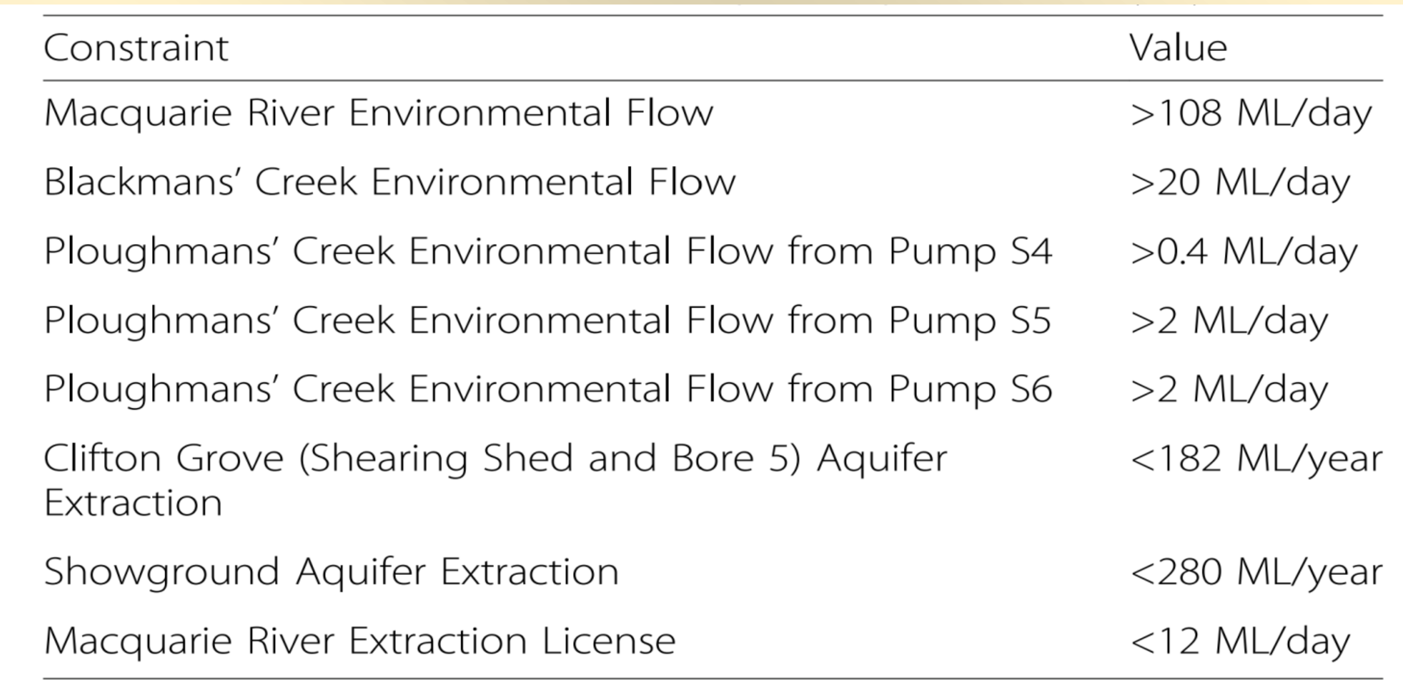


The Figure above shows a schematic process diagram of the system: (note that the ‘Shearing Shed’ bore and ‘Bore 5’ are grouped as the ‘Clifton Grove’)

Water from the Ploughman’s Creek Storm water Scheme is treated through a series of wetlands, and then combined with water from the Blackman’s Swamp Creek Storm water Scheme. This water is then treated and used to top up Suma Park reservoir. Due to the severely low water supply levels during the drought, the Council immediately sought approval for use of the storm water schemes on a permanent basis. Water quality monitoring is undertaken to ensure the respect of regulations of the Office for Water, the New South Wales Environmental Protection Authority and the Ministry of Health. The Macquarie pipeline transfers water from the adjacent Macquarie River catchment to Suma Park reservoir. It is 38 km long and requires more than 600 m of pumping head. Each of the three pumping stations has **two pumps** operating in parallel. Water from the groundwater bores is pumped first to balancing storages and then to Suma Park reservoir, with a combined licensed volume of 462 ML per year. Water from all of the sources is combined in Suma Park reservoir and treated at a water treatment plant before reaching the consumers. The Orange City Council wishes optimizing the operation of this while delivering a secure yield from Suma Park Dam. In addition to the primary objective of minimizing energy cost, there are objectives of **minimization of spill** from Suma Park reservoir, **minimization of (perceived) environmental impact (greenhouse gases emissions)**, **maximization of (perceived) water quality**, and **minimization of**

energy use, per volume of water pumped. The Council's goal is to minimize spill to ensure water and energy are not wasted by pumping from one of the three alternative sources to fill up Suma Park reservoir just before a rainfall event that would supply water from the natural catchment at no cost or energy output.

As this system supplies potable demands, it is undesirable to apply water restrictions to consumers, thus minimizing time spent in restrictions is important. The constraints of the problem include environmental flows for the Macquarie River (downstream of the pumping station off take point) and storm water schemes, a water source license for the Macquarie River and extraction limits on the groundwater bores.



Constraint	Value
Macquarie River Environmental Flow	>108 ML/day
Blackmans' Creek Environmental Flow	>20 ML/day
Ploughmans' Creek Environmental Flow from Pump S4	>0.4 ML/day
Ploughmans' Creek Environmental Flow from Pump S5	>2 ML/day
Ploughmans' Creek Environmental Flow from Pump S6	>2 ML/day
Clifton Grove (Shearing Shed and Bore 5) Aquifer Extraction	<182 ML/year
Showground Aquifer Extraction	<280 ML/year
Macquarie River Extraction License	<12 ML/day

Energy optimization formulation:

Blinco et al developed a framework to help set up the optimization procedure and identify the components and data to be modeled. Although the model that has been built takes into account all possible objectives of the system, the authors presented results focused on the **minimization of energy consumption**.

For this case study, operating decisions consist of **trigger levels** in the various storages. These types of decision variables are based on the control system available at each pump station (based on storage levels and not on time of the day) and the fact that the controls have to be defined for an operational horizon of 1 year or longer. As all of the pump stations are consisted of two or more pumps disposed in parallel, having different trigger level values may have a large impact on the operating point of the pumps and thereby their energy consumption. In order to assess the performance of different tank trigger levels, the infrastructure studied includes the natural and urban catchments for the surface water and stormwater systems respectively, Suma Park reservoir, pipelines and pumps in the groundwater, Macquarie River and storm water systems, and wetlands and storage ponds in the storm water systems. The authors made it clear that the system could be modelled using hydrologic models, mass balance models, and/or hydraulic models. The choice of which model(s) will be used depends on the objectives and the processes to be modelled, on the available data and the **computational times**. In particular, hydrologic modeling part (transformation of rainfall to runoff) was easier thanks to previous studies by the Orange City Council. Hydraulic models are usually used for short term operations: pump energy costs can be computed accurately based on the hydraulic equations. Mass balance modeling is usually used for assessing the system in long term operations, as it can quickly compute the water available after evaporation and other losses in the system have happened and after minimum release of environmental flows. It cannot, however, take into account the **non-linearity** in the hydraulic equations. While hydraulic simulation is more convenient for the pumping stations in the system as they have multiple pumps and sometimes have connected pipelines, mass balance models must be used to calculate the additional processes, such as evaporation and the release of minimum environmental flows that need to be taken into account given the long duration of the simulation. During an optimization process, simulating each possible solution using both a mass balance and a hydraulic model would increase the computational time, particularly if data transfer between the two models was required. The authors then suggested that the primary simulation tool should be a hydraulic solver. Rainfall runoff modeling could be done pre-optimization, and additional code added to a hydraulic model to account for functionality of a mass balance model. This would allow for consideration of the evaporation from and rainfall directly to reservoirs, demand changes based on water restrictions and environmental flows that depend on the combined volume of two reservoirs

(Spring Creek and Suma Park), losses due to infiltration when transferring water between reservoirs and peak power demand charges. The authors were confronted by another issue which is the simulation **time step**. Using a shorter time step will improve the accuracy of this hydraulic analysis and often results in feasible optimization times for storages that empty or fill in the span of one to two days (which is the case for the stormwater ponds and Macquarie pipeline balancing storages). Since the variations in the water levels can have a period of several years, simulating the behavior of Suma Park dam can be more difficult. Therefore, the computation with a short time step become prohibitively long. A balance needs to be found between using a short enough time step for the detailed hydraulics and a long simulation time for the large storages without having a prohibitively large computational time. Given the data availability (there is 118 years of rainfall and inflow data available, with a daily time step) the time step chosen **is 1 day**. Which was automatically shortened by the hydraulic solver chosen by the authors (**EPANET**), the model of the real system has been simplified in order to avoid additional computational times. In particular, given that the levels in the balancing storages along the Macquarie pipeline vary rapidly, these storages were removed and the pipeline simulated with two parallel pumps, each representing the equivalent of the three stages of pumping (that is, the pump curves for Pumps M1a and b were adjusted such that they represented Pumps M2a, M3a and Pumps M2b, M3b as well). This simplification is considered acceptable as the pumps in series in the Macquarie pipeline will usually be operated at the same time, given that each pump will still be controlled also by the level of Suma Park Dam. Longer computational times were also caused by the small storages after the groundwater bores. The pumps used for extraction from the aquifers (Pumps G1a, G2a and G3a) operate at relatively consistent rates, and as such they could be removed from the model and their energy use accounted for relative to the volume pumped from the second pump in each system (Pumps G1b, G2b and G3b respectively). To take into account the limited volume available from the groundwater bores, the storage tanks in the groundwater system each had a volume equivalent to a year’s allocation for the respective bores. As well as the operating point of the pumps changing depending on the number of pumps used in parallel, there may be slight differences in efficiency and therefore energy use, and thus including all pumps here provided more accuracy. All of the pumps included in this method were controlled using rule-based controls in EPANET, with conditions on levels in one or more storages and conditions on time. For the Macquarie pumps, there were also conditions based on the flow of the river to ensure that no water would be taken when the water level was below a certain value. There were four possible decision variables for each pump, a lower and upper trigger level in both the peak and off-peak time. For optimization of energy use, only two are required, as peak and off-peak tariffs are not considered. As the model was set up for other objectives including cost, which does use a peak and off-peak electricity tariff, the possibility to choose different trigger levels in different periods was added. A maximum of 15 pump switches per day per pump were allowed, and the end level of Suma Park Dam was constrained to 16 m (to be approximately the same as the start level). Based on license conditions, Macquarie River water can only be used when the Suma Park Dam level is below 90%, so choices for Pump M1a and M1b trigger levels in Suma Park Dam are more constrained than for other pumps.

Yes! The added value is palpable

Energy optimization results Minimization of pump energy use over the longer term is presented here as an example of optimization of this system. The authors note that the system is simulated over 1 year, at a daily time step in EPANET. Additional computer code was added to the EPANET hydraulic simulation to take into account other process such as rainfall to and evaporation from storages. This code essentially adds a mass balance component to the hydraulic simulation. Historical rainfall for the catchments in the system was modelled in MUSIC hydrologic software to develop inflow series for the ponds and reservoirs.

NSGAII (Non-dominated Sorting Genetic Algorithm II) software was used for the optimization, with five random seeds, a population size of 50, 100 generations and probabilities of crossover and mutation of 0.8 and 0.02 respectively. In the best solution found, the system used a total of 793 MWh of energy over the entire year. Pumping from the Macquarie is very energy intensive so this is only used at the very end of the simulation when the level in Suma Park Dam is very low, in order to achieve the end target level constraint (Figs. 1.1 and 1.2).

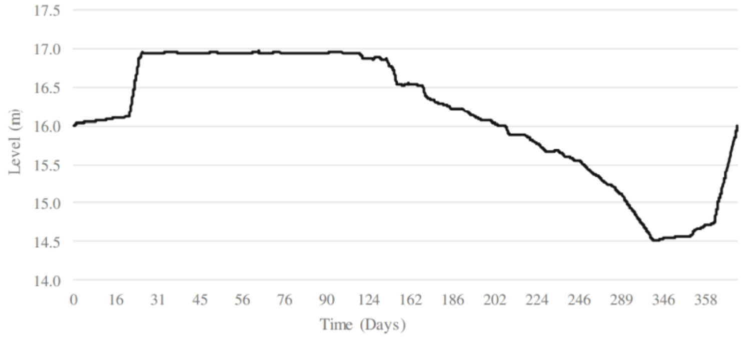


Fig. 1.1 Variation in Suma Park Dam level for the energy optimal solution

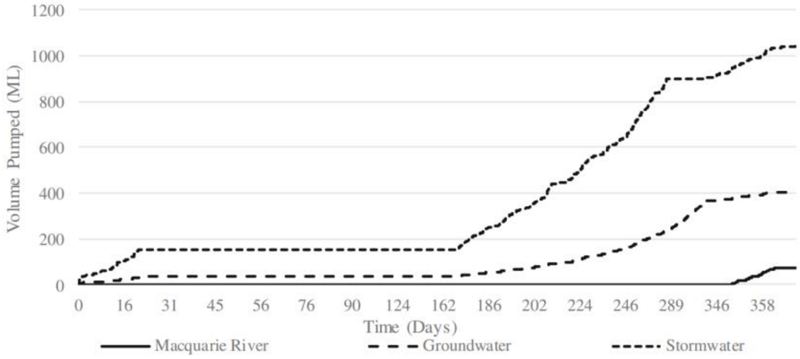


Fig. 1.2 Volume pumped from each source to Suma Park Dam for the energy optimal solution

Groundwater and stormwater sources are used initially to increase the level of Suma Park Dam to its maximum, and then not used again until around Day 160 when the level in the dam has dropped again. Only one of the Macquarie pumps is used, as, despite operating at a lower energy efficiency point, it uses less energy overall than operating two pumps in parallel. In dryer years, both pumps may need to be utilized in order to ensure supply to Suma Park Dam. Nearly all of the available groundwater license is used; G1 and G2 have a combined license of 180 ML/ year, and G3 280 ML/year. Groundwater is more energy intensive than stormwater, but, it can be used at any time throughout the year, while stormwater is reliant of inflow. Most of the stormwater provided to Suma Park Dam came from the Blackman's Creek scheme (S1) rather than the Ploughman's Creek scheme (S4, S5 and S6). While the storage capacity of the Blackman's Creek scheme is much lower, the pump capacity and energy efficiency is much greater than in the Ploughman's Creek scheme, so it provides more water.

5. Can this model be implemented in Morocco?

As a country entering a phase of water scarcity in the few next years, Morocco understood this constraint and went on constructing numerous big capacity dams. However, in regions (southern ones especially) where rainfall is undependable, transportation of water from other regions is the only solution left. Which raises the following question, can optimization techniques such as the one detailed previously help authorities make wiser decisions when it comes to finding alternative water resources?

The answer is a definite **yes,** while the calculation time might be relatively longer, and the cost might be higher, the long term results are worth it. Enabling social fruition, minimizing the use of energy and thus its cost and its impact on the environment, are simple examples among many others of the benefits. Furthermore, comparing dimensions between the Macquarie River in the study and the largest river in Morocco (Sebou) shows that the Macquarie River is way longer, thus making it a plus reason to adopt this method by looking for alternative water sources and optimizing the flow of water to a certain point where the reservoir should be constructed. For more accurate and precise results, I personally think that the optimization process should be done by specialized **design offices**, be it in building constructions or water infrastructures.

One more thing:

This is a successful example of applied optimization techniques to a real world complex engineering problem, which is not only complex in itself(multiple objective functions, trigger levels, pressure settings, valve settings) but also conditioned by more complex external factors(climate change, demand on water, electricity infrastructures, government policy, international regulation) and so on. As an **enlargement** opportunity for the subject, we can apply the same framework to serve other purposes such as harvesting storm-water from an urban creek, and using it as non-potable supply for **irrigation** of sporting fields and reserves. Or we can exploit it to monitor the water distributed to households according to the use, storm-water for non-potable usage (toilet, irrigation, laundry… for instance)

6. Conclusion:

Optimization is clearly a must and a helpful step to be integrated in all the solutions suggested for civil engineering problems, we saw only one example, but the literature out there is flabbergasting. Stevanovic et al. [4] addressed the importance of reducing excessive fuel consumption and vehicular emission on urban streets. To handle this problem traditionally signal timing is optimized. They proposed a tool based on integrating three previously developed tools called as VISSIM, CMEM, and VISGAOST to optimize signal timings and minimizing fuel consumption and CO2 emission. Whereas Sabatino et al. [5] proposed a framework to eliminate the effect of structural failure of highway bridges on the economy, society, and the environment. Genetic Algorithm based optimization procedure was used to reach the optimal solution in terms of maintenance interventions. The validity of the proposed approach was tested on an existing highway bridge located in Colorado.

7. References:

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5. Sabatino S, Dan M Frangopol, Dong Y (2015) Sustainability-informed maintenance optimization of highway bridges considering multiattribute utility and risk attitude. Engineering Structures 102.